

Excited two-dimensional magnetopolaron states in quantum well of resonant tunnel junction

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Tunnel spectroscopy is used to probe the electronic structure in GaAs quantum well of resonant tunnel junction over wide range of energies and magnetic fields normal to layers. Spin degenerated high Landau levels ($N = 2 \div 7$) are found to be drastically renormalised near energies when the longitudinal optical-phonon ($\hbar\omega_{LO}$) and cyclotron energy ($\hbar\omega_C$) are satisfied condition $\hbar\omega_{LO} = m\hbar\omega_C$, where $m = 1, 2, 3$. This renormalisation is attributed to formation of resonant magnetopolarons, i.e. mixing of high index Landau levels by strong interaction of electrons at Landau level states with LO-phonons.

In polar semiconductors, such as GaAs, electrons interact with LO phonons to form polarons, i.e. the bare electron states are renormalized. If a magnetic field \mathbf{B} is applied perpendicular to the plane of the GaAs quantum well, 2D electron states are quantized into Landau levels (LL) of index N . Filling of empty Landau levels in the QW by tunnelling current causes excitation of resonant magnetopolarons^{1,2} when resonant condition $n\hbar\omega_{LO} = m\hbar\omega_C$, where n, m are integers, is satisfied. The resulting magnetopolarons can be measured experimentally by monitoring density of states in the quantum well by tunnel spectroscopy. Previously only interaction of ground Landau state $N = 0$ with $N = 1$ and $N = 2$ ones via LO-phonons have been detected by means of phonon assisted tunnelling spectroscopy³. It was displayed as anticrossing of the position of the peaks related to the double phonon assisted tunnelling into LL ($N = 0$) and single phonon assisted tunnelling into LL ($N = 1, 2$) in the fan diagram.

In this work we present studies of electron structure of the QW in a magnetic field normal to the well plane by means of tunnel spectroscopy. The Al-GaAs/GaAs/AlGaAs heterostructure was double barrier structure incorporating a layer of InAs quantum dots (QD) in the center of the well. The dots are charged and create a considerable amount of disorder in the well. In this case the number of elastic scattering assisted tunnelling events with only energy conservation, but not momentum conservation is increased considerably. It means that direct tunnelling between different LL's in the emitter and collector is permitted and one can monitor the density of states in a magnetic field in

the QW by means of both elastic and inelastic tunnelling spectroscopy. The phonon assisted tunnelling channel is opened independently of sample quality. As the result we have found strong interaction between LL's of different indices ($N = 2 \div 7$) in the well near energies when the longitudinal optical-phonon ($\hbar\omega_{LO}$) and cyclotron energy ($\hbar\omega_C$) are satisfied condition $\hbar\omega_{LO} = m\hbar\omega_C$, where $m = 1, 2, 3$. This was attributed to formation of resonant magnetopolaron states, i.e. mixing of different LLs by interaction with LO-phonons.

Samples grown by MBE comprised (in the order of growth): a lightly Si-doped, 300-nm-thick GaAs layer ($N_d = 3 \cdot 10^{18} \text{ cm}^{-3}$); a 50.4-nm-thick GaAs layer ($N_d = 2 \cdot 10^{17} \text{ cm}^{-3}$); a 50.4-nm-thick undoped GaAs spacer layer; a 8.3-nm-thick $Al_{0.4}Ga_{0.6}As$ barrier layer; a 5.6 nm undoped GaAs layer; a 1.8 monolayer (ML) InAs (with growth rate 0.13 ML/s to form InAs QD); a 5.6-nm-thick undoped GaAs layer; a 8.3-nm-thick $Al_{0.4}Ga_{0.6}As$ barrier; a 50.4 nm undoped GaAs; a 50.4-nm-thick GaAs layer ($N_d = 2 \cdot 10^{17} \text{ cm}^{-3}$); and a 300-nm-thick GaAs layer ($N_d = 3 \cdot 10^{18}$) cap-layer. The samples were characterised by photoluminescence (PL) spectroscopy, which confirmed the existence of the corresponding QD or WL emission. Ohmic contacts were obtained by successive deposition of AuGe/Ni/Au layers and subsequent annealing. Mesa structures, with diameter between 20 μm and 400 μm , were fabricated by conventional chemical etching.

The band diagram of the structure under voltage bias is shown in Figure 1(a). With the application of a sufficient bias to the structure, an accumulation layer is formed adjacent to the barrier, which serves as two-

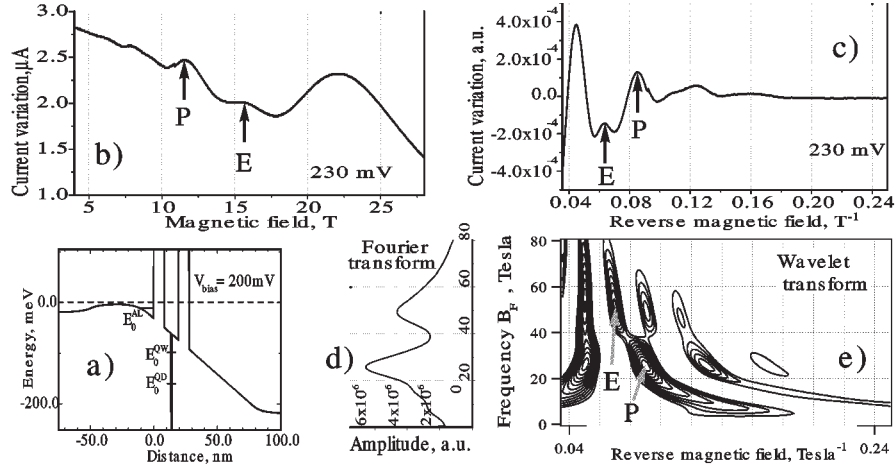


FIG. 1: (a) The band diagram of the structure under voltage bias; (b) variation of tunnelling current versus magnetic field at $V_{bias} = 230$ mV; (c) variation of tunnelling current versus reverse magnetic field at $V_{bias} = 230$ mV; (d) result of Fourier transform; (e) result of WL transform.

dimensional emitter. The details of resonant tunnelling through this double barrier structures with disorder introduced by QD was published earlier⁴. The tunnelling current oscillates with varying magnetic field with constant bias applied to structure (Fig. 1(b)). Peaks are observed, corresponding to tunnelling into Landau states of the ground subband in the well with and without phonon emission. We analyse only the data for fields above $4T$, when only the lowest energy Landau level is occupied in the emitter. All measurements were carried out at temperature $T = 4K$.

Careful analysis of the experimental data at each V_{bias} allowed us to identify all peaks in a magnetotunnelling spectrum. Three different techniques have been used to do this: identification of peak position in $1/B$ vs. LL number, Fourier analysis, and more sophisticated wavelet analysis. The wavelet analysis⁴ is a mathematical tool, which allows to decompose a signal in the locally confined waves (Wavelets).

The general expression for WL transform is $(Tf)(a, b) = |a|^{-\frac{1}{2}} \int dt f(t) \psi(\frac{t-b}{a})$, where $\psi(t)$ is so called "mother" wavelet function. The transform result is a function of two variables. Parameter $(\frac{1}{a})$ is analog of frequency in the Fourier transform. Each $\psi(\frac{t-b}{a})$ is localized around $t = b$. For WL decomposition of our experimental data we have used the Morlet⁵ "mother" function $\psi(t) = (\exp(i\gamma t) - \exp(-\frac{\gamma^2}{2})) \exp(-\frac{t^2}{2})$, which is a trigonometric function modulated by Gaussian. The parameter γ determines the number of oscillations one wants to use for the analysis and should be optimised in each specific case. In more details the procedure of wavelet analysis is described in paper⁶.

The result of WL analysis of tunnelling spectra recorded at 230 mV is shown in Figure 1. Fig. 1(b) and Fig. 1(c) show recorded signal versus magnetic field and reverse magnetic field respectively. The result of Fourier transform is shown in Fig 1(d). Figure 1(e)

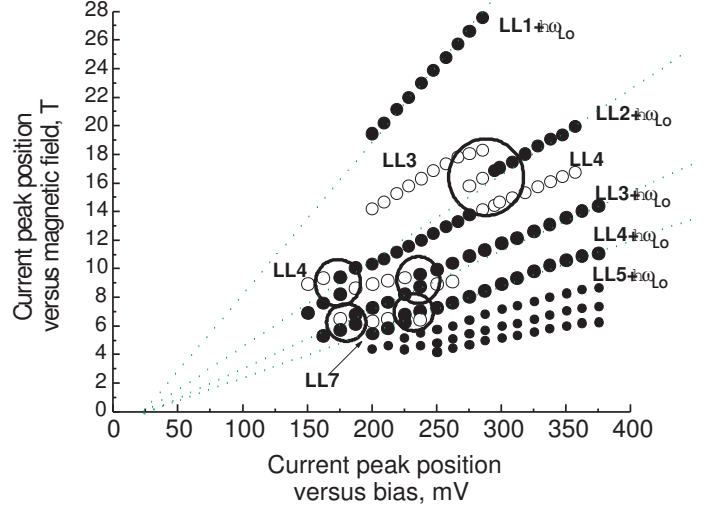


FIG. 2: Fan diagram summarised peak positions versus magnetic field in tunnelling spectra. Solid circles - position of peaks due to phonon assisted tunnelling. Open circles - direct tunnelling from the ground Landau level $N = 0$ in the emitter to Landau level of higher indexes in the quantum well. In the fan diagram it is easy to see regions where different levels are anticrossing. These regions are indicated by circles.

shows result of WL transform. This is the 3-dimensional picture, where the amplitude $A_{WL} = Re[(Tf)(\frac{1}{a}, b)]$ of the Wavelet transform (z-axis) is presented versus frequency (y-axis) and the inverse magnetic field (x-axis). As usual tunnelling with and without phonon emission⁷ results in two sets of oscillations periodical in reverse magnetic field in tunnelling spectrum at constant bias, with frequencies $B_F^{LO} = \frac{m^*}{e\hbar}(E_{Em} - E_{QW} - \hbar\omega_{LO})$ and $B_F^{EL} = \frac{m^*}{e\hbar}(E_{Em} - E_{QW})$ respectively. Here m^* and e are the effective mass and charge of an electron; \hbar is the Plank constant; E_{Em} , E_{QW} , are the energies of the

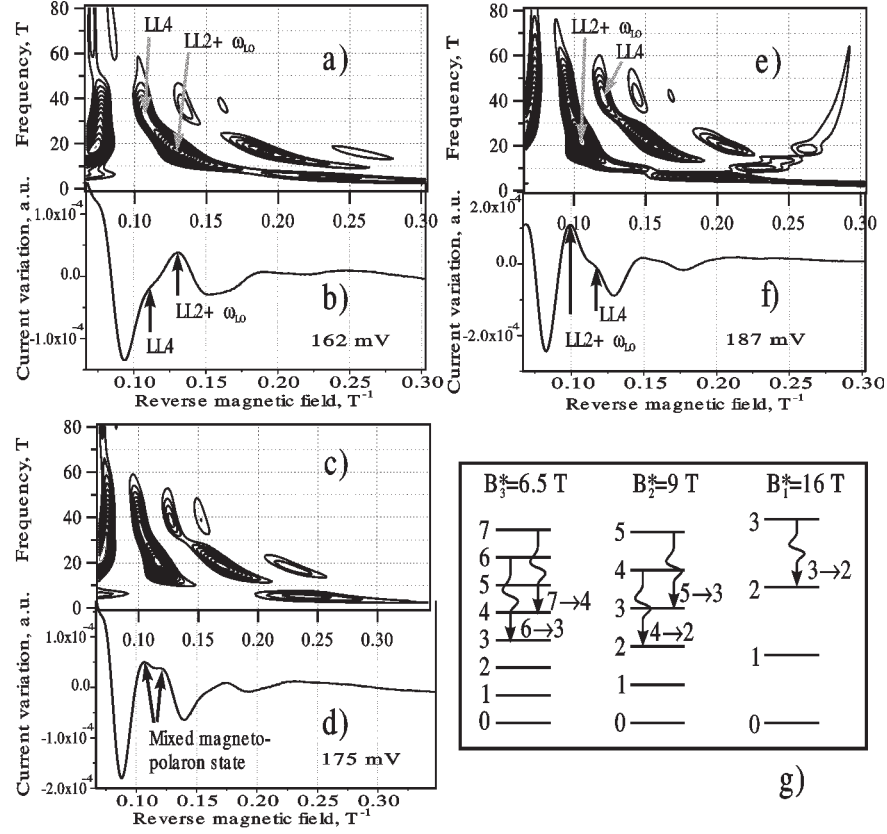


FIG. 3: This figure illustrates strong interaction between $N=2$ and $N=4$ Landau levels in magnetic field around $B=10$ T when $2\hbar\omega_C = \hbar\omega_{LO}$, details are in the text. (a) Wavelet transform of the tunnelling spectra at $V_{bias} = 162$ mV; (c) at $V_{bias} = 175$ mV; (e) at $V_{bias} = 187$ mV; (b) variation of tunnelling current versus reverse magnetic field for $V_{bias} = 162$ mV; (d) for $V_{bias} = 175$ mV; (f) for $V_{bias} = 187$ mV; (g) schematic presentation of the identified magnetopolaron states.

ground quasibound states in the emitter and in the quantum well (QW) respectively, $\hbar\omega_{LO}$ is the longitudinal optical phonon energy. Peaks in the tunnelling spectrum related to phonon assisted tunnelling into LL belong to low frequency set of oscillation and the elastic scattering peaks to high frequency set. Fourier transform spectrum (Fig. 1(d)) shows evidently two frequencies separated by $\Delta B = 21.4$ T. Than $\Delta B \frac{e\hbar}{m^*} = 37$ meV, which is equal to energy of LO-phonon (36 meV) in GaAs with good accuracy as expected. Wavelet transform permits one to determine the origin of each peak in the tunnelling spectrum. For example, arrows labelled by "E" in Figures 1(b) and 1(c) indicate the same peak. Appropriate maximum in the amplitude A_{WL} of the Wavelet transform (Figure 1(e)), also indicated by arrow "E". Wavelet data indicate that the peak belongs to the high frequency set of oscillations and therefore is related to the elastic tunnelling into LL with $N=3$. The LL index could be easily determined by standard procedure. In the same manner one can conclude that peak labelled by "P" appears due to the phonon assisted tunnelling into LL with $N=2$. (More precisely one should say that peak "P" is the superposition of two peaks, one with higher amplitude related with phonon assisted tunnelling and another

of the smaller amplitude with direct tunnelling into LL with $N=4$). In this way we have identified all the peaks in the tunnelling spectra at different bias voltages. Fan diagram in Figure 2 summarised peak positions versus magnetic field in tunnelling spectra. Solid circles - position of peaks due to phonon assisted tunnelling. Open circles - direct tunnelling from the ground Landau level $N=0$ in the emitter to Landau level of higher indexes in the quantum well.

Strong interaction between LL of different indexes have been observed in tunnelling spectra $\hbar\omega_{LO} = m\hbar\omega_C$ with $m=1, 2, 3$. The details of this interaction between $N=2$ and $N=4$ Landau levels ($m=2$) is shown in Figure 3, as example. Tunnelling spectra versus reverse magnetic field for three different biases are presented in Figures 3(b), (d), and (f). Figures 3(a), (c), (e) show Wavelet transforms of the tunnelling spectra, respectively. Since these peaks move versus bias with different velocity, one could expect that without interaction they should cross at the intermediate bias voltage, $V_{bias} = 175$ mV in this case. Contrary we see typical anticrossing behaviour of the peaks, first, the exchange of oscillator intensity, second, the same peak is related to direct tunnelling on one side or phonon assisted-tunnelling on another side away

from strong interaction point. Circles in the fan diagram (Figure 2) indicate the regions where different levels are anticrossing. Next magnetopolaron states have been identified in this work:

$$\begin{aligned}\hbar\omega_{LO} &= \hbar\omega_C = E_{LL3} - E_{LL2} \\ \hbar\omega_{LO} &= 2\hbar\omega_C = E_{LL5} - E_{LL3} = E_{LL4} - E_{LL2} \\ \hbar\omega_{LO} &= 3\hbar\omega_C = E_{LL7} - E_{LL4} = E_{LL6} - E_{LL3}\end{aligned}$$

This is illustrated in Figure 3(g).

In conclusion, we have observed and identified a set of two-dimensional resonant excited magnetopolaron states, i.e. mixing of different high indexes Landau levels by

optical phonons, for electron tunnelling into a quantum well with embedded quantum dots.

Acknowledgments

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¹ S. D. Sarma, Phys. Rev. Lett. **52**, 859 (1984).

² F. Peeters and J. Devreese, Phys. Rev. **B 31**, 3689 (1985).

³ G.S.Boebinger, A. Levi, S. Schmitt-Rink, A. Passner, L. Pfeiffer, and K. West, Phys. Rev. Lett. **65**, 235 (1990).

⁴ Yu.V.Dubrovskii, E. Vdovin, A. Patane, P. Brunkov, I. Larkin, L. Eaves, P. Main, D. Maude, J.-C. Portal, D. Ivanov, et al., Nanotechnology **12**, 491 (2001).

⁵ A. Louis, P. Maass, and A. Rieder, *Wavelets: Theory and Applications* (John Wiley& Sons Ltd, 1997).

⁶ (The MathWorks, <http://www.mathworks.com/products/wavelet/description/overview.shtml>).

⁷ M. Chukalina, H. Funke, and Y. Dubrovskii, Low Temperature Physics **30**, 930 (2004).